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MINIATURE ACCELEROMETER WITH A FUSED QUARTZ SUSPENSION

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A MINIATURE ACCELEROMETER WITH A FUSED QUARTZ SUSPENSION*

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Abstract

A miniature accelerometer has been constructed which employs a fused-quartz torsion fiber suspension. The purpose was to demonstrate a small yet reasonably accurate component, and at the same time explore the possibilities of fused quartz in a specific application. The accelerometer is based on the well-known force-balance servo principle, and employs a photoelectric pickoff. The design and construction of the device are described.

Variation in null offset of $\pm 1/2 \times 10^{-4}$ g was observed over a 130-day period; linearity error to 1 g of 3×10^{-5} g rms ($1\,\sigma$) was observed.

It appears that the torsion fiber suspension can provide a stable support with unusually small uncertainty torques, which is extremely rugged and stable.

I. Introduction

This paper describes a miniature accelerometer which has been constructed as a supporting research project at the Jet Propulsion Laboratory. The development has not been associated with any specific program or schedule; rather, it has been an inquiry into new or different techniques which are not in common use in the development of accurate

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acceleration sensing devices. The specific purpose was to investigate the capability of fused quartz in this application and to demonstrate an unusually small instrument which still maintains the high level of accuracy necessary for inertial guidance. The advantages of small size in such an instrument are immediately apparent.

Exceptional dimensional stability, ideal elastic properties, and high strength in small cross sections are qualities that make fused quartz an attractive material for this application (1, 2). Several techniques (1, 3) are available for fabricating very small assemblies from it. The smaller the suspension is made the more rugged it will become, since fiber strength increases sharply with decreasing size; consequently, there is a very real advantage in selecting a small size.

An important part of the work to date has been the development of technique to successfully fabricate such an instrument. Torsion fibers are the only convenient suspension means suited to fabrication from fused quartz, so it may be well to point out a few of the characteristics of torsion suspensions and compare them to the types more familiar in inertial components. The spring rate of a torsion suspension can be made very small compared to a flexure suspension of the same strength. When one considers the extremely small size in which quartz fibers can be formed, really remarkable uncertainty torque levels can be achieved. In common with flexure suspensions, the torsion element can be made to conduct and carry current to the suspended mass, thus eliminating flex leads. These advantages are offset by lack of rigidity perpendicular to the torsion axis and its associated low-frequency resonance. The instrument design must provide room for the suspended mass to move and, probably, sufficient damping to control the resonance if operation in a severe vibration environment is contemplated.

The well-known servo force-balance principle has been employed to obtain accurate force readout. In general, this principle utilizes a sensing mass mounted in a suspension so that it is free to move in one direction but is restricted as strongly and rigidly as possible in the plane perpendicular to this direction. Forces applied by the suspension in the direction of free motion, or sensitive axis, are made as small as possible. Any inertial force imposed on the mass in the direction of the input axis is balanced by a force generated by an electrical current flowing through a conductor in a fixed magnetic field. The linear relationship between current and force becomes the means by which acceleration can be accurately read out. Displacement of the mass caused by an unbalance between inertial and electromagnetic force is sensed by a position pickoff, which controls the forcing current by means of an amplifier in such a way that the mass remains at a null position with respect to the case of the instrument.

Since there is no viscous damping available in this particular instrument, its force-rebalance servo must employ rate feedback for stability. The performance of this servo under large random noise inputs has been observed.

II. Design and Construction

The actual mechanization of the suspension, magnet, and pickoff is shown schematically in Fig. 1. A photoelectric pickoff is almost a necessity because the small mass of the pendulum requires that reaction torques be extremely small. Forces applied to the mass by the position-sensing device will be read out as an error in acceleration. The suspension is of the pendulum type, pivoting about the point at which the torsion fibers attach. The mass is concentrated mostly in a straight cylindrical rod or fiber and is attached to the much smaller torsion fibers by two tapered quartz rods, forming a horseshoe. The straight section at the horseshoe is immersed in the magnetic field, and the entire pendulum as well as the torsion fibers is made to conduct by an evaporated gold coating. The magnetic field is oriented perpendicular to the length of the straight cylindrical section and in the plane of the horseshoe, so that the electromagnetic force generated perpendicular to both produces torque about the torsion axis.

This geometry realizes the minimum sensitivity to the position of the current-carrying rod in the field. A uniform field is created between two plane pole pieces, allowing the rod to move in the gap with minimum change of scale factor and also allowing it to tilt with only a cosine relationship relating force to the angle of tilt.

The mechanical spring restraint obtained is essentially negligible, being very much smaller than the restraint in similar instruments using flexure suspensions. With any reasonable degree of stability in the associated electronics, unwanted torques from the suspension will be insignificant in comparison with other uncertainty torques.

The U-shaped quartz pendulum is hung by torsion fibers from a supporting structure which is also built-up from quartz rod. The whole assembly thus becomes an integral piece of fused quartz when completed, ensuring mechanical stability. An outline of the suspension, including some basic dimensions, is shown in Fig. 2. The 3-μ diameter chosen for the torsion fibers is small enough to be difficult to work with without specialized technique, but is larger than the limiting size (approximately 1 μ) for working with microtorch flames (1 μ = 0.000040 in.).

A gap has been provided, as shown, in which 1000-centistoke fluid is held by surface tension around each torsion fiber near the ends attached to the pendulum. The fluid effectively damps the inherent resonance of the torsion type of suspension.

Attempts were made to observe mechanical torques introduced by the drops of fluid, but none were found. The fluid in one suspension has been watched for one year, with no visible loss, but care must be taken that the quartz rods forming the gap are clean.

The significant parameters of the suspension are summarized below:

Mass of pendulum	$M = 0.53$ mg
Moment of inertia	$J = 0.12 \times 10^{-3}$ gm-cm^2
Pendulosity	$P = 0.24$ dyne-cm/g
Computed torsional spring restraint	$k_s = 3 \times 10^{-3}$ dyne-cm/rad
Preload tension in fiber	$T_0 = 200$ mg

The numbers quoted above are those which have been selected for a suspension scaled to provide a full-scale range of ±10 g in the completed instrument. As shown in Fig. 2, the mass of the pendulum is fairly well concentrated in the straight rod section located between the pole pieces. If the assumption is made that all the mass is there, then a simple relationship is available to give the pendulum mass as a function of full-scale range R.

$$m(\text{mg}) = \frac{R}{5}(\text{g}) \qquad (1)$$

A film of gold to carry the torquing current is deposited on the whole suspension by conventional vacuum evaporation techniques. The gold film is broken in two places to provide isolation of the torquer circuit from the case of the instrument. The rest of the gold merely prevents static charges from building up on the surface of the quartz. The gold film is estimated to be of the order of 1/4 μ thick.

The only limitation presented by the gold electrically is on the 3-μ fibers themselves. The maximum current which could be passed through a suspension having a gold coating of a thickness such that its resistance was 700 ohms was determined experimentally, at 14 $\pm$ 0.5 ma. The total resistance of the two fibers was arbitrarily put at 500 Ω in the first suspensions. Since then, lower resistance values have been tried, down to 80 Ω, and no adverse effects on the elastic properties of the suspension have been observed. Current through the fibers has been limited to 10 ma maximum, and no failures have occurred from normal operation. However, transients from ac test equipment can easily exceed 10 ma, and special fuses have been used to protect the suspension. They are made from a short (1/2 mm) section of quartz fiber slightly smaller than that used in the suspension itself, coated with nearly the same thickness of gold. Fuses of 12-14 ma rating and 40-75 Ω resistance were obtained in this manner.

The pickoff used is a dc push-pull photoelectric type employing silicon "solar cell" photodiodes. The operation of the pickoff is illustrated in Fig. 3. The pendulum is placed between two fixed opaque shutters, leaving a narrow gap on each side, and the pendulum and shutter arrangement is illuminated uniformly from, say, above. The separate but identical photodiodes then can detect motion of the pendulum which narrows one gap and widens the other.

The photodiodes are formed from a single wafer of silicon in order to obtain the maximum degree of symmetry. An etched or scribed line through the junction layer of the solar cell serves to separate the diodes. Symmetry is desirable because it minimizes response to light intensity and temperature variations. A few of the characteristics of the diodes are as follows.**

**Electro-Optical Systems, Inc., Pasadena, Calif.

Sensitivity	$8 \mu a$ ft-c^{-1}cm^{-2} (Short circuit output current, tungsten light)
Source impedance	30 k ohms
Size (each diode)	1/2 x 1 x 0.16 mm

Symmetry, or differences in output between the two diodes on a wafer, was 5% over a two-to-one variation in light intensity and a temperature range from 75 to 180°F.

Miniature incandescent lamps were obtained† to excite the pickoff. Their characteristics are as follows:

Diameter	0.100 in.
Length	0.187 in.
Filament rating	3 v, 60 ma

Other miniature lamps are available.‡ These tiny lamps have never been damaged by the vibration testing which the accelerometer has undergone. The light from the filament is collected by a condensing lens mounted in the pole piece; the lens has a 2.3-mm diameter, a 1.9-mm focal length, and is focused on the photodiode through a tapered hole in the pole piece. This condensing system has made a more efficient pickoff than the lucite light pipe condenser which was tried earlier.

Figure 4 shows the principal dimensions of the magnetic circuit. The magnets are cut from a standard channel horseshoe, of Alnico V alloy. The pole pieces are Allegheny-Ludlum No. 4750.

An exploded view showing all the parts except the suspension is shown in Fig. 5. The assembled instrument is shown in Fig. 6. The pole pieces, magnets, and suspension are located by the squared holes in the body.

Since there is no damping in the accelerometer proper, phase lead must be provided by the amplifier in order to make the servo restoring loop stable. This has been done by placing the proper impedance in the feedback loop of a dc amplifier. A schematic diagram of the amplifier used for ordinary

† No. CM 8-666; Chicago Miniature Lamp Co., Chicago, Ill.
‡ American Cystoscope Makers, Inc., Pelham Manor, New York; Sylvania, Salem, Mass.

laboratory testing is given in Fig. 7. The push-pull arrangement is used to minimize drift due to temperature changes. The input transistors must be selected for match and, in addition, they are operated at low base current ($3\mu a$) to further reduce drift. With these precautions, it is felt that an equivalent input drift of $\pm 0.2\mu a$ during a temperature change from 75 to 180°F can be realized in practice. Drift of $\pm 0.1\mu a$ over the same temperature range has been ovserved.

The 2N330 transistor in the input has been introduced in order to control the base current flowing into the input pair of transistors while allowing the current from the pickoff to vary according to changes in lamp voltage. This arrangement greatly reduces common mode rejection by the amplifier. The bench test data which follow were obtained with this amplifier.

A disadvantage of the circuit is that its phase lead is lost if the amplifier saturates. The system is normally stable after a saturating transient, but a different amplifier must be used for shake testing. The solution was to take out the rate signal before the last (saturating) stage. Another stage of gain was placed between the differential stages shown and the output emitter follower.

III. Test Data

Many of the tests performed were of a general type applicable to any accelerometer and have been described elsewhere. Therefore, no discussion is presented here on the methods by which the data have been obtained.

Gain and frequency response curves have been taken in order to ensure that the force-balance servo will function as intended. The output of the pickoff, measured as current flowing in a 1-K load attached directly to the photo cells is given in Fig. 8. The output is plotted against deflection of the pendulum in milliradians. The output current from the amplifier into a 1-K load, which is identical to the current which would flow through the pendulum in closed loop operation, is plotted against pendulum deflection in Fig. 9. The frequency response of the amplifier is shown in Fig. 10, and the frequency vs relative gain of the whole accelerometer loop is plotted in Fig. 11.

The amplifier gain is adjusted so that the steady-state crosscoupling, or standoff error of the servo, is 0.2 millirad/g.

The scale factor of the torquer is 0.87 ma/g or, in absolute units, approximately 0.28 dyne-cm/ma.

The performance of the complete accelerometer has been measured in terms of quantities defined as follows:

k_0 = null offset (the output of the accelerometer in terms of g, with zero acceleration input)
k_1 = scale factor (the average ratio of input acceleration to output voltage)
N_a = null angle (the angle between the sensitive axis--zero input--and an arbitrary reference in the case)
Δ = linearity error (defined below)
a = applied acceleration, g
V_0 = accelerometer output, volt

Several of these quantities are interrelated, as follows:

$$V_0 = k_1 (k_0 + a + \Delta)$$

Test data have been accumulated for a continuous period of four months on one unit. The data presented have been obtained on this unit except where noted. No compensation for the temperature of the magnets or for permanent null offset has been used. Both can be satisfactorily compensated. The accuracy with which an unknown acceleration can be measured depends, therefore, only on the variation observed in the null offset, rather than on its absolute value. The term null uncertainty will be used to designate change in null offset.

Null offset has been measured frequently over the entire duration of the test period and is plotted vs time in Fig. 12, showing an over-all average of $37.3 \pm 0.5 \times 10^{-4}$g. Two other suspensions have previously been tested for a period of several weeks, resulting in null offsets of 10.4 $\pm 0.5 \times 10^{-4}$ and $2.9 \pm 0.5 \times 10^{-4}$ g. The null uncertainty can therefore be set at approximately $1/2 \times 10^{-4}$ g for a period of up to four months. All tests performed on each suspension in which the accelerometer was operated in its normal configuration have been included in the above averages.

Short-term stability of null offset has also been determined for the period of approximately an hour needed to obtain one set of data. Stability of null angle and scale factor was also measured; 1σ values from six such tests have been averaged arithmetically to obtain typical values:

$$\frac{\delta k_1}{k_1} = \pm 0.3 \times 10^{-4} \qquad \text{(scale factor)}$$

$$\delta k_0 = \pm 0.5 \times 10^{-4}\ g \qquad \text{(null uncertainty)}$$

$$\delta N_a = \pm 0.6 \times 10^{-4}\ \text{rad} \qquad \text{(null angle)}$$

It is interesting to note that short-term and long-term null uncertainty values are the same.

Temperature tests were conducted in which the accelerometer was placed in an oven, but the dc amplifier was not. The observed dependence of null offset and null angle on temperature is plotted in Fig. 13. The curves shown for null angle represent data which are somewhat better than average. An additional term must be included in the change of null angle which is a function of the amplifier temperature. Typically, 0.2 to 0.4 millirad could be expected from a change of 100° F in amplifier temperature. A reasonable figure which might be obtained with proper technique for the over-all drift including both amplifier and pickoff is felt to be 0.2 - 0.4 millirad for the 100° F range (room temperature to 180° F). The observed variation in null offset is larger than expected and is explained in a subsequent section in this paper.

If the pickoff null is moved intentionally, the dependence of null offset and scale factor on pendulum position is obtained. The results of such a test are plotted in Fig. 14. Provision is made in a special preamplifier for shifting the null position to cover the complete range between stops if desired. The slope of the null offset vs null angle is, of course, the effective spring constant. The measured value is -0.015 g/rad. The scale factor curve is actually a measure of the dependence of the magnetic field on position in the gap. The unit (g/rad) used for quoting spring constant means that the torque produced by the indicated number of g's acting on the known pendulosity will deflect the pendulum through 1 radian. For comparison, the computed mechanical spring rate of the fiber is +0.01 g/rad.

Linearity data below 1 g were obtained on a dividing head. In Fig. 15, the error Δ, defined above as the indicated acceleration minus the applied acceleration, is plotted in the range of -1 g to +1 g. The accelerometer was mounted with the torsion fiber perpendicular to the dividing head axis to eliminate crosscoupling.

Linearity above 1 g was checked on a centrifuge, and the results are shown in Fig. 16. In this test, it is scale factor in arbitrary units, rather than error, which is plotted against input acceleration.

Shake testing with white noise vibration in the band of 20 to 1500 cps has been performed in all three axes. Sinewave vibration has also been applied on all three axes at a 5-g level in a search over the same frequency band. No significant resonances were observed in the output of the accelerometer. The noise vibration was applied along both axes which lie perpendicular to the sensitive axis up to a level of 18 g rms with no major effect on the operation of the accelerometer. The rectification (that is, the change in the dc component of its output induced by the vibration) was measured. For vibration applied parallel to the torsion fiber, the rectification coefficient was 4×10^{-6} g/g^2; for vibration applied perpendicular to both torsion fiber and sensitive axis, the same coefficient was 0.8×10^{-6} g/g^2.

When the vibration was applied parallel to the sensitive axis, the pendulum could be observed to hit the stops at 10 to 12 g rms. Up to that point, the rectification was found to be 3×10^{-6} g/g^2. The amplifier which was used saturated at ±21 ma torquer current. This limitation of torquing capability is felt to be the reason that the force balance servo fails to retain capture above a certain level of noise input. The level at which the pendulum strikes is not the point at which the amplifier first saturates, but rather is at a much higher level, roughly twice the threshold of amplifier saturation.

IV. Interpretation

A general understanding of the advantages and limitations of the design concept of the torsion fiber accelerometer has been developed in obtaining the foregoing results. These constraints will be discussed, data which appear unusual will be explained insofar as possible, and areas for possible improvement will be discussed.

The characteristic flexibility of the torsion fiber type of suspension has been pointed out. Experimentally its influence has been felt primarily in the area of crosscoupling, which has been 0.7 - 1.0 millirad/g in instruments with a 10 g range. The most likely reason appears to be that one pole piece has been made narrower than the other as a convenient way to shape the magnetic field. A field gradient across the gap has resulted; since the whole pendulum must sag under the influence of gravity when the sensitive axis is aligned horizontal, a small variation must occur in scale factor proportional to the acceleration applied perpendicular to both the sensitive axis and torsion fiber. This introduces an error term which is of the same form as crosscoupling due to low amplifier gain and cannot be distinguished from it (except possibly for sign). An instrument will be built with symmetrical pole pieces in order to test this hypothesis. With proper design, but using the same suspension, it is felt that 0.2 millirad/g is a reasonable value to expect.

The rigidity of the 10-g suspension to forces applied perpendicular to the torsion fiber and the sensitive axis can be estimated. Using 200-mg tension, one obtains 800 dyne/ cm^{-1} for this transverse spring rate. Expressed in terms of g, this means the mass sags 0.006 mm when subjected to 1 g transverse acceleration. If a force is applied in the direction of the torsion fiber instead of perpendicular to it, an angular sag will occur, but the maximum displacement of a point on the pendulum will be of the same order of magnitude. Although more than desirable, displacements of this magnitude do not seem to be prohibitive. The resonant frequency associated with the transverse spring rate is at about 200 cps. Not much can be done to increase it because of limitations imposed by the tensile strength of the fibers and the square root relationship of frequency to tension.

As shown by shake test data, there does not seem to be any difficulty from transient effects in a suspension which has the fluid drops placed around the fiber.

The direct-coupled pickoff and amplifier used make the instrument susceptible to another type of misalignment caused by electronic drifts. An over-all uncertainty of 0.2 millirad, consistent with the value quoted for mechanical flexure, should be attainable with ordinary good technique. In many applications it is possible to orient the instrument so that the uncertainty in alignment of the sensitive axis causes minimum system error. This uncertainty exists only on one plane, since alignment in the plane containing the torsion fiber and the nominal sensitive axis is mechanically determined and is observed to be very precise, i.e., much better than 0.1 millirad.

An unexpected result has been the discovery that significant magnetic forces are exerted on the fused quartz torquer because of its diamagnetic susceptibility. Being diamagnetic, quartz will tend to be expelled from a nonuniform magnetic field, with a force proportional to the gradient of the field. The forces involved are extremely small, but the forces which are being measured are also small. Therefore, the magnetic field around the location of the pendulum must be extremely uniform. Quantitatively, this requirement is more stringent than the well-known requirement imposed by the need for a constant scale factor in a torquer which, in practice, moves in the field somewhat under applied acceleration.

Referring to Fig. 14, the magnetic field (scale factor) is seen to have a gradient along the direction of the pendulum motion, no doubt caused by imperfect alignment of the pole pieces. This gradient is responsible for the large null offset observed, since it can be shown to yield the correct force by computation. Also, a small local minimum exists in the field at the center because a hole has been put into one pole piece to allow light to enter the pickoff. If no effort is made to correct it, an elastic-type restraint having a magnitude of ~ 0.7 g/rad is imposed on the pendulum by the second derivative of the field strength. No adverse effect on short-term performance has been observed from either type of force, but it nevertheless appears advisable to minimize them. Experience to date indicated that permanent null offset less than 10×10^{-4} g before compensation and a spring constant less than 0.1 g/rad in magnitude can be achieved by holding pole piece alignment and shape to within one or two tenths of a mil. It is very possible that the observed variation in null torque with temperature is reflecting a change in magnetic field gradient. If this is true, lowering the magnitude of the force can reasonably be expected to lower the variation which is induced by temperature changes, in addition to making independent compensation to less than 10^{-4} g practical.

The effective spring constant can be controlled by varying the width of the pole pieces, becoming less (algebraically) as their width is decreased. The slight local minimum caused by the hole which admits the pickoff excitation light is counteracted by the central maximum in the field formed between two surfaces of limited width. The possibility of a negative spring restraint, as observed in Fig. 14, is seen to exist. The presence of a negative spring restraint when a slight field minimum (superimposed on a larger gradient) is indicated by the scale factor curve cannot now be quantitatively explained. A likely reason is that the quartz pendulum rod is not small compared with the dimensions of the field variations. The spring force can be correctly estimated by theory when it is larger (+0.7 g/rad).

There are two limitations of a more basic nature. The first is that the absolute scale factor stability depends on the degree to which the strength of permanent magnets can be held constant. This is a problem associated with all force balance instruments employing permanent magnets, and will not be discussed further.

The second limitation is that the fibers, with their conducting coatings, have a very definite maximum current-carrying capacity, which results in a maximum force capability of the torquer. This limits the range which can be obtained with a reasonable pendulum size and mass. In addition, a limit is placed on the maximum tolerable noise vibration input during operation, as is seen from the discussion of the shake tests. The action of the servo under large noise input is not fully understood, but it does not seem reasonable to expect more than perhaps 50% improvement in maximum tolerable vibration input for a given suspension.

If accurate performance under vibration environment proves to be a limiting factor, the well-known techniques of fluid-damped or floated components are, of course, available for use with this type of suspension. It should be emphasized that the vibration problem is one of having the accelerometer operate to specification in a severe vibration environment. The present units survive severe vibration without any significant changes in their characteristics.

On the other hand, a number of advantages are obtained. The instrument is inherently a simple one. There are no close machining tolerances (less than 0.001 in.) in the instrument which has been tested, and none seem necessary except for control of the dimensions and alignment of the pole pieces. The suspension carries all its mechanical stability requirements in itself, since it is an integral assembly of fused quartz. It must either remain unchanged or be broken. The suspension as a unit can be interchanged between metal parts.

The null stability which has been observed over a period of months, $1/2 \times 10^{-4}$ g, is a strong point, and there is no reason to believe some further improvement cannot be made. Especially in applications involving lower full-scale range where the effective magnetic field could be lowered, one might expect better performance.

No uncertainty torque that could be attributed to the suspension was observed. Of course, it is difficult to separate the several causes of null torque, but the fact that its long-term uncertainty was no worse than the short-term uncertainty tends to rule out an effect such as creep which occurs over an extended period. A random effect such as convection currents in the air surrounding the mass seems a more likely cause.

Perhaps surprisingly, the suspension has been found to be quite rugged. Although it employs fibers only 3 μ in diameter, it does not need to be handled with special care. In fact, a dummy was tested without being mounted in an accelerometer, and required 36 g of noise vibration to break it.

An advantage does stem from the characteristic lack of rigidity of the torsion suspension. The mass is contained in a gap and is mechanically surrounded on all sides. There is enough flexibility in the suspension to permit the mass to strike a surrounding part before the torsion fibers are stressed near the breaking point. In other words, the mass is mechanically caged so that it cannot break the weak link in the suspension, the fiber. Since quartz cannot be permanently strained short of actual fracture, the adjustment and subsequent operation of such a suspension should be unaffected by large shocks.

In summarizing, possible areas of advantageous application can be mentioned. Applications in which the acceleration to be measured is not large and is not accompanied by large (10 g or 10 g rms, respectively) vibration; together with a requirement for less than 10^{-4} g null stability over long periods seem most suitable. These requirements are typical of guidance systems for large ballistic missiles. Very large accelerations or vibration applied before the measuring period should have no ill effects. Since the dimensions of the instrument are so small, application to very low range measurements ($<$ 0.1 g full scale) seems appropriate, because the proof mass would still remain relatively small. However, testing in the Earth's 1-g field would present a serious problem.

It is also interesting to note that the accelerometer will make an excellent device to sense level with no special alteration. The low spring restraint and good stability of the suspension make it possible to sense level to an estimated accuracy of about 0.1 sec of arc. To do so the accelerometer is mounted as a horizontal pendulum, that is, with the torsion axis vertical, and is operated open loop. A magnification of pendulum motion over actual tilt of perhaps 3 orders of magnitude can be obtained, reducing the effect of pickoff null drift in proportion.

V. Conclusions

The practicability of constructing a small accelerometer, using a fused quartz torsion fiber suspension, which is both rugged and accurate has been demonstrated.

No attempt has been made to package either the accelerometer proper or the electronics in the minimum possible space. The weight and volume of the accelerometer lies chiefly in the magnetic circuit, but it should still be possible to package it in one-half of the present volume, using the same suspension and magnetic field.

To date, three sets of metal parts have been fabricated, and a total of perhaps ten quartz suspensions have been operated.

A recurring problem with fused quartz is the difficulty of procuring fused-quartz assemblies. This should not always be the controlling consideration in its use. The techniques used, although unfamiliar, are not as difficult as the high-precision machine-shop techniques ordinarily used for precision components. The suspensions described have been made successfully at JPL without previous experience in the practical problem of working fused quartz. The technique had to be learned by the instrument specialist who performed the work as he went along.

Because the suspension fibers and the mass have been made extremely small, the uncertainty torques are much smaller in an absolute sense than those familiar to the component field. A null uncertainty of 10^{-4} g corresponds to a torque of 0.25×10^{-4} dyne-cm, or $0.05\,\mu$g weight, expressed as a force. The maximum measurable torque is 2.5 dyne-cm, or approximately 5 mg weight, as a force.

A possible area of usefulness therefore exists outside the inertial guidance field. The operating principle could prove valuable in any measurement of very small forces which must be made quickly.

Acknowledgment

A great deal of appreciation is due W. H. Hermann, whose facility with the many new techniques involved helped to surmount many difficulties. His skill with the fused-quartz fabrication was indispensable. Thanks are also due to E. Bates for much of the assembly work, and to H. Ailslieger for the testing.

The basic concept for the dc amplifier is due to D. Slaughter.

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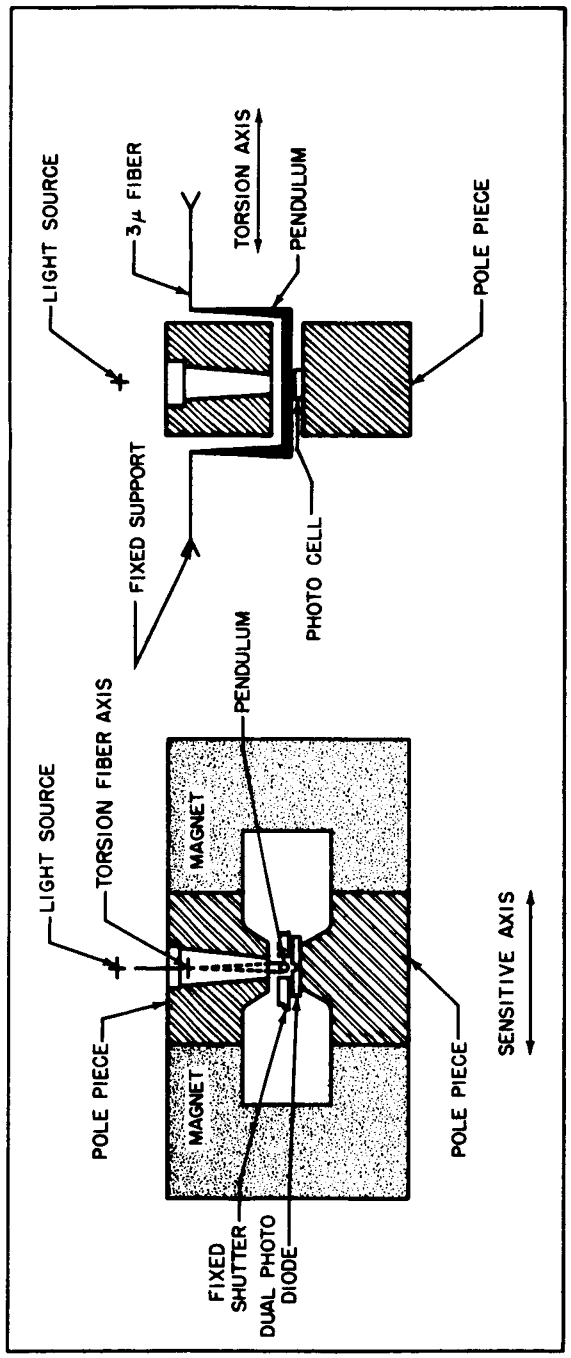

Fig. 1. A Diagrammatic View of the Accelerometer

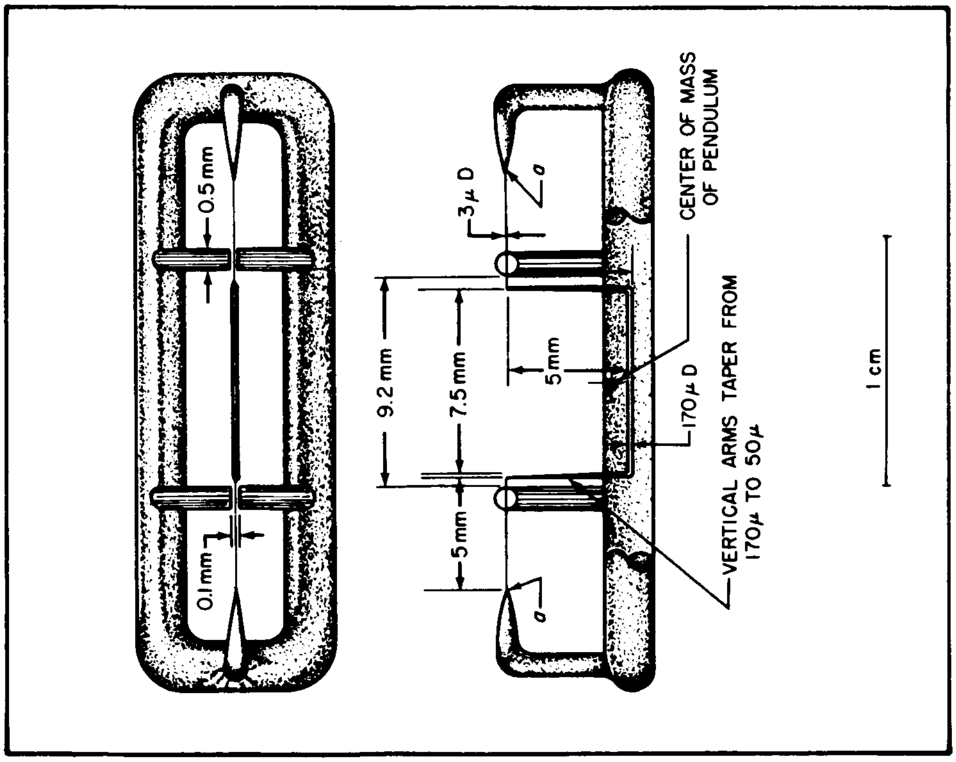

Fig. 2. The Fused Quartz Suspension

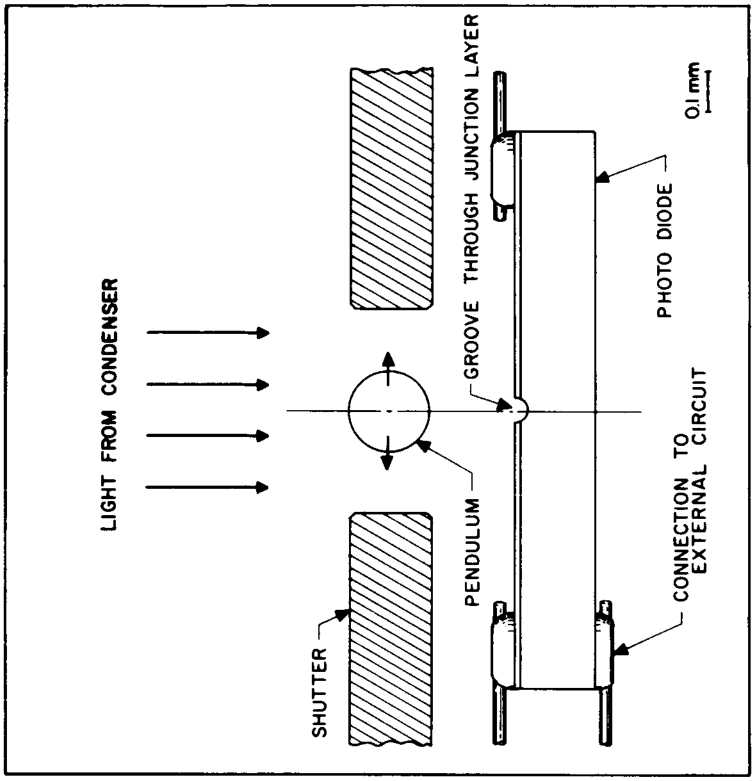

Fig. 3. A Diagrammatic View Showing the Pickoff Elements

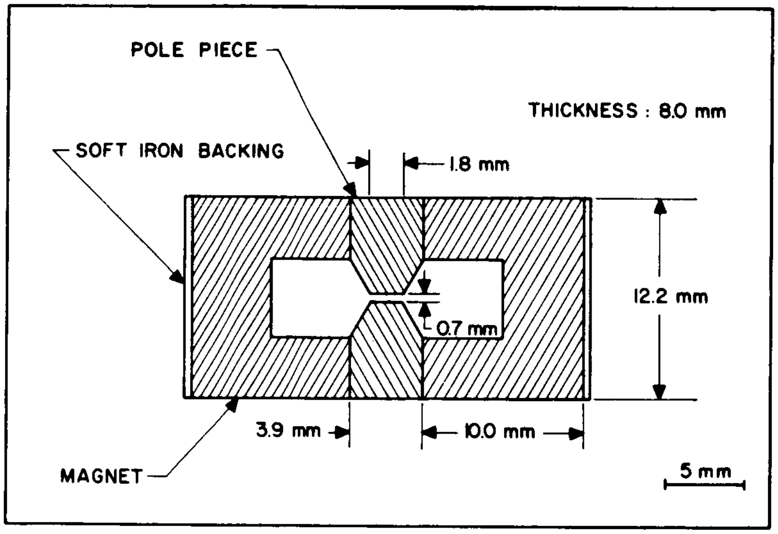

Fig. 4. Sketch of the Magnetic Circuit

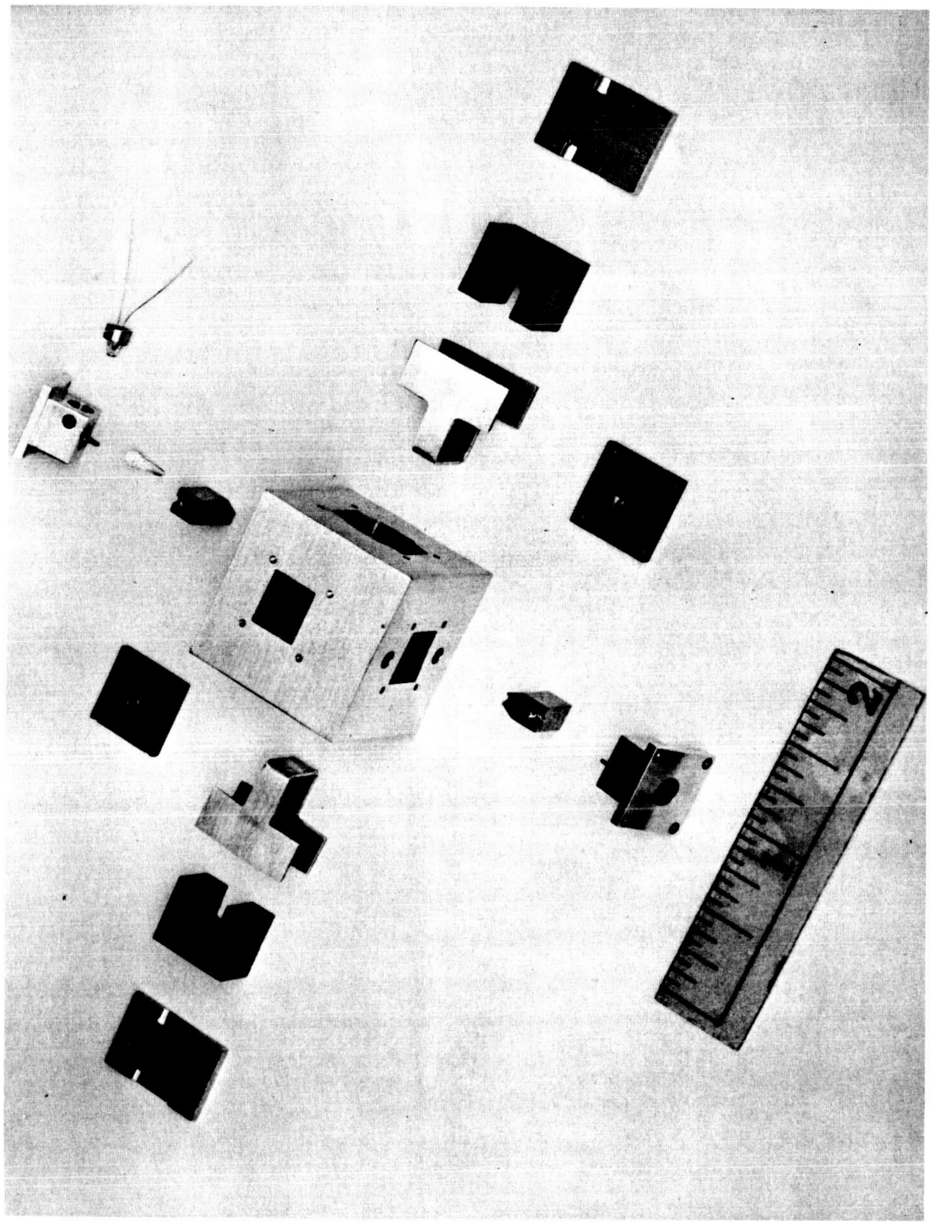

Fig. 5. Exploded View of Mechanical Parts

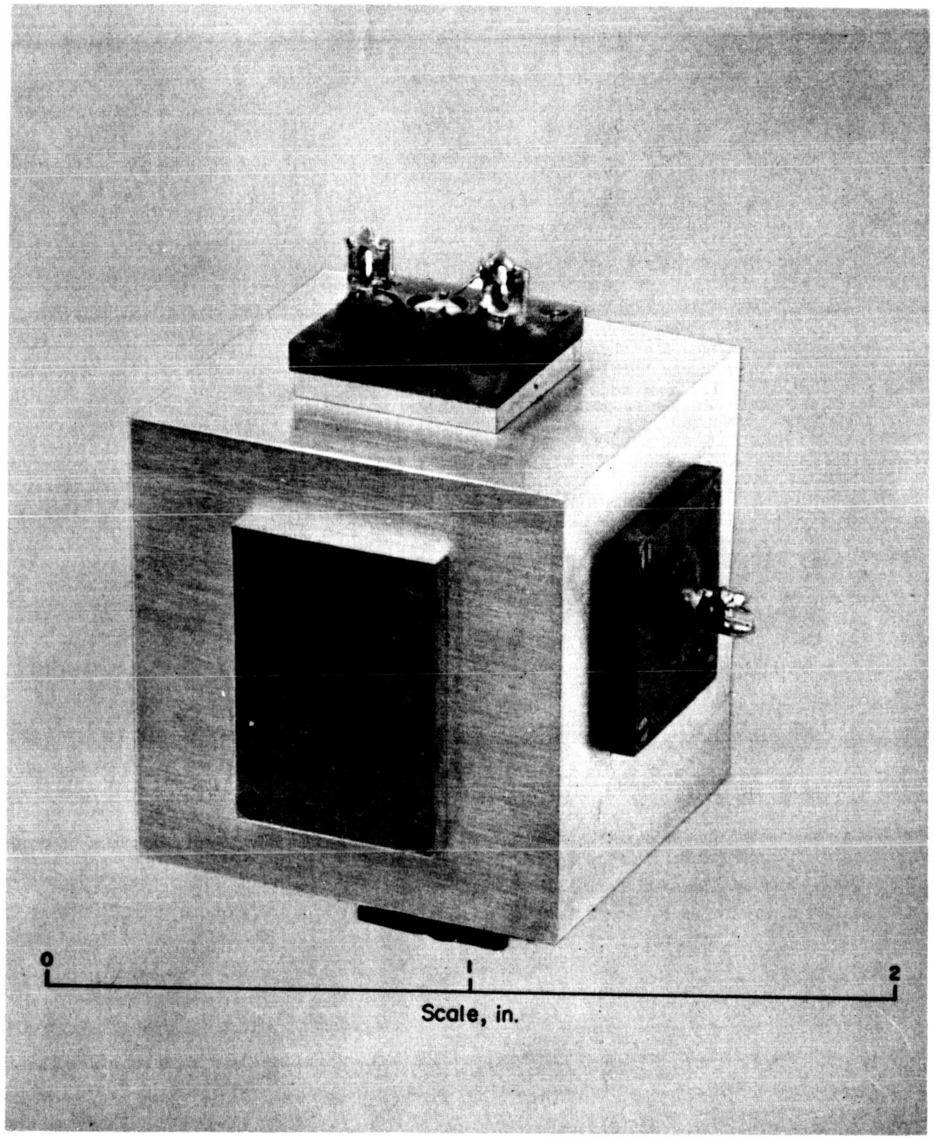

Fig. 6. The Assembled Accelerometer

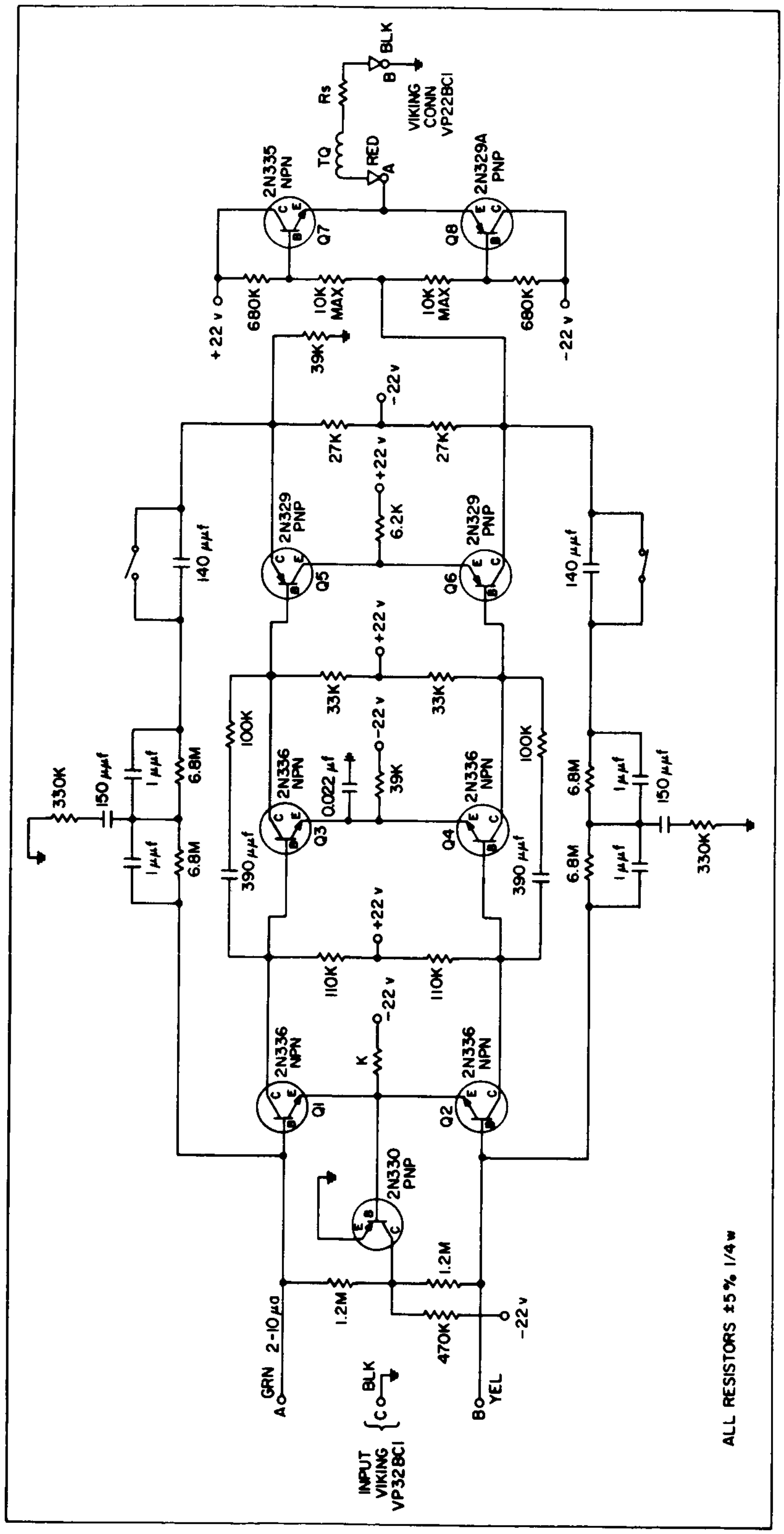

Fig. 7. Schematic Diagram of Servo Amplifier Used in Testing

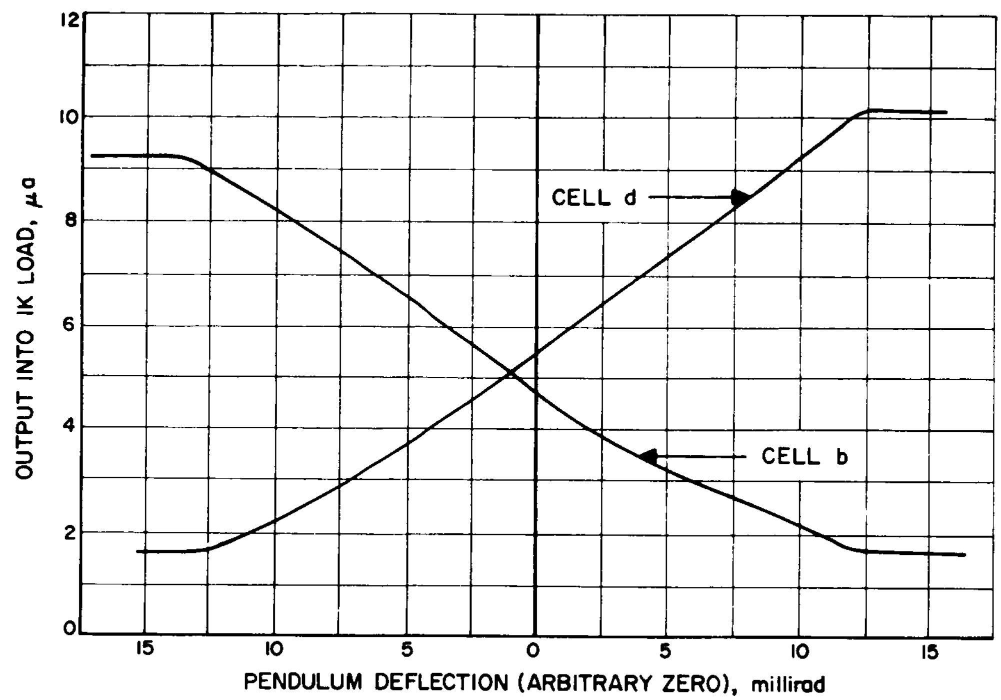

Fig. 8. Pickoff Response as a Function of Pendulum Deflection

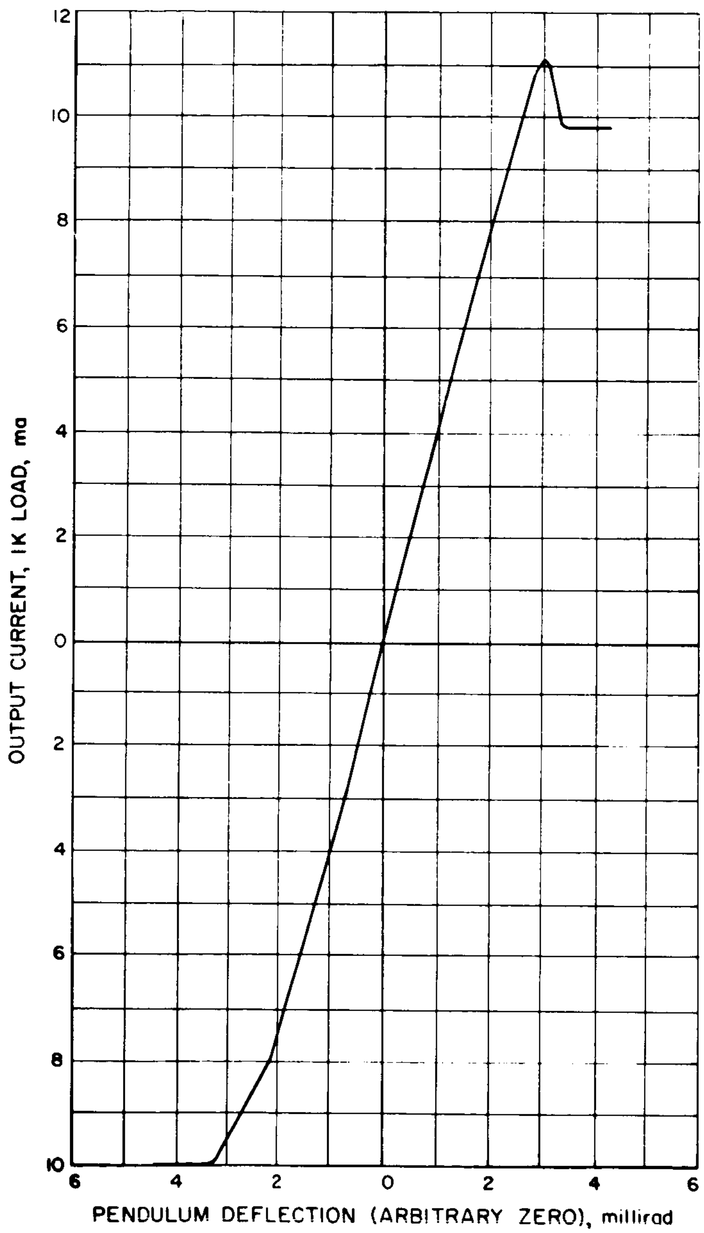

Fig. 9. Response of Amplifier as a Function of Pendulum Deflection

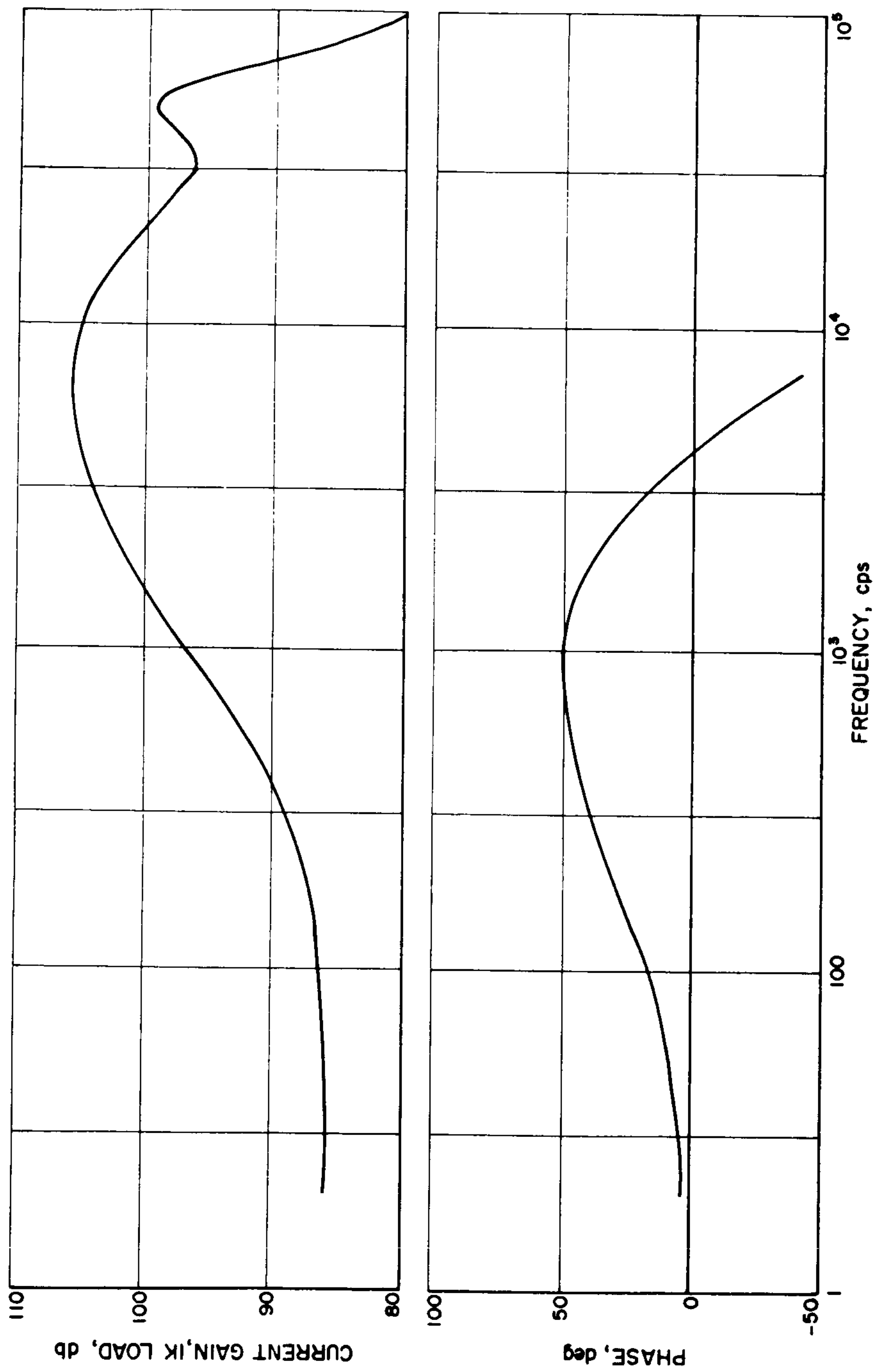

Fig. 10. Frequency Response of Amplifier

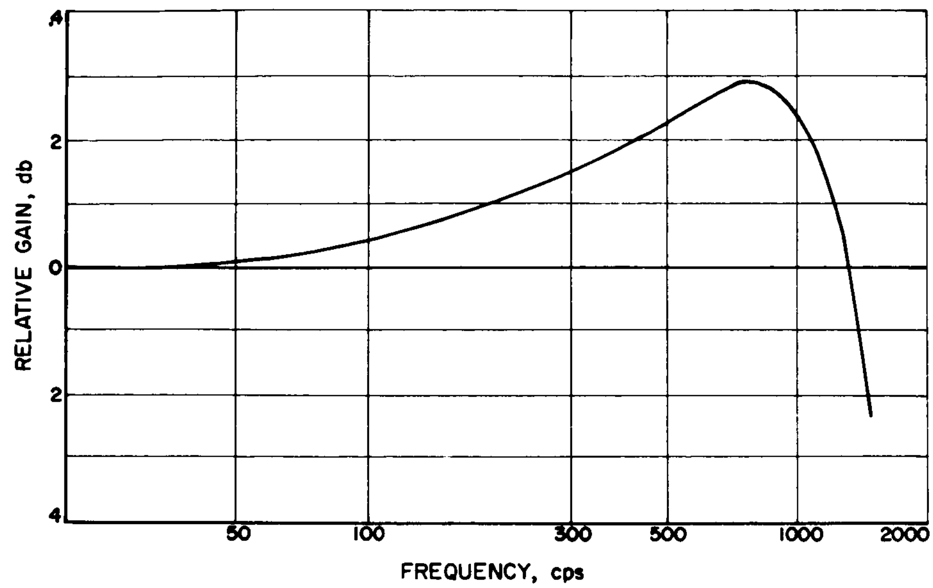

Fig. 11. Frequency vs Relative Gain of the Accelerometer

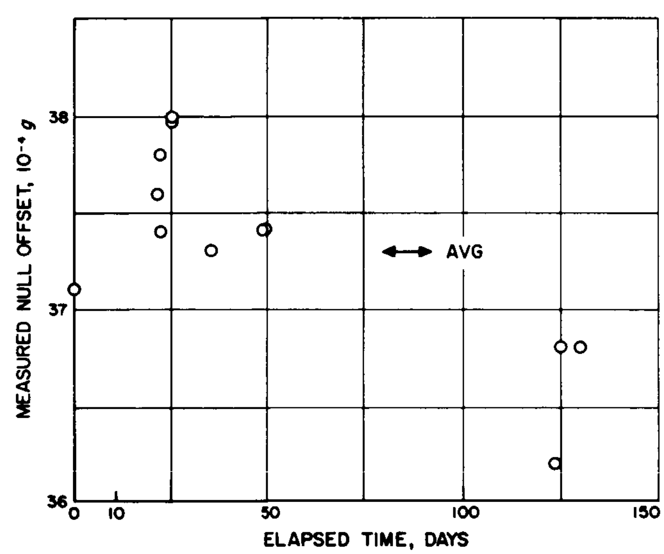

Fig. 12. Null Offset as a Function of Time, Over a 130-day Period

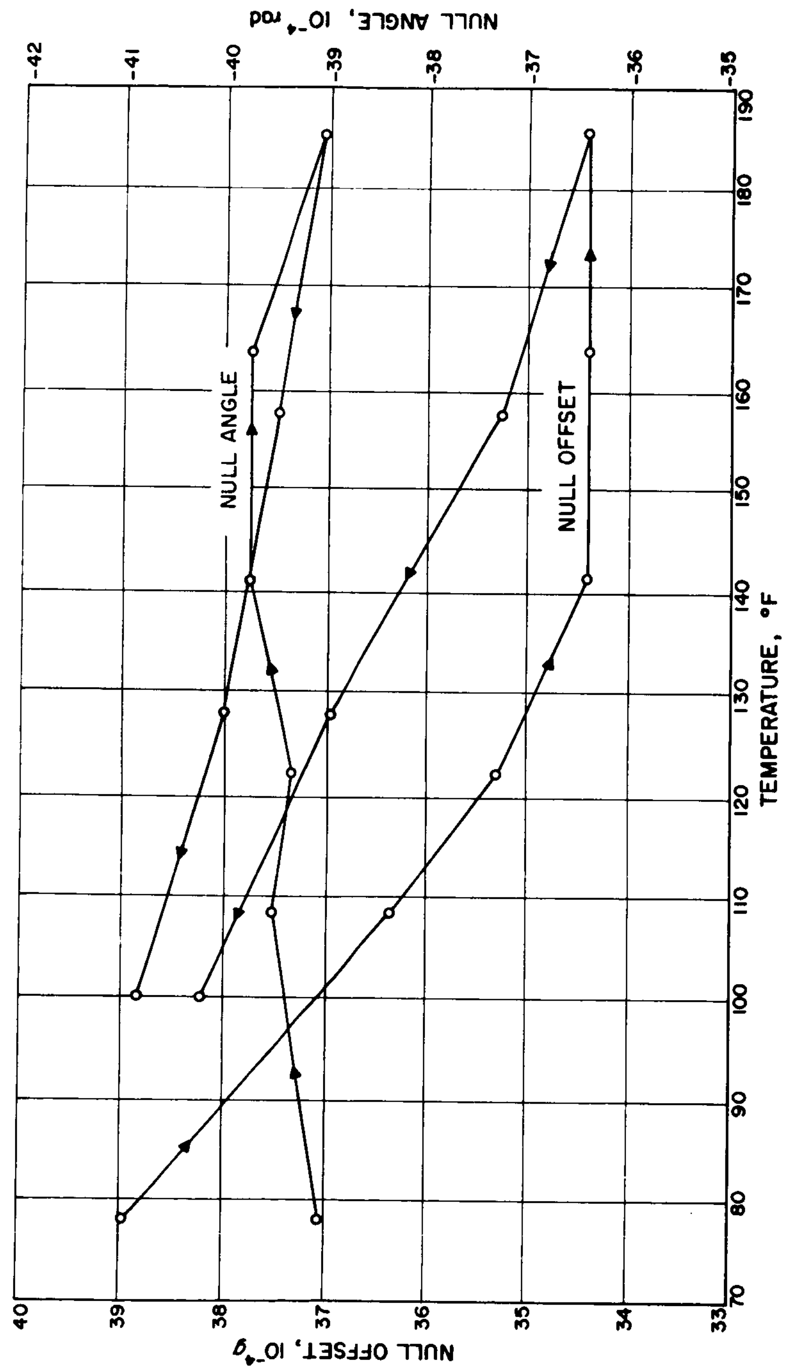

Fig. 13. Null Offset and Null Angle vs Temperature of Accelerometer

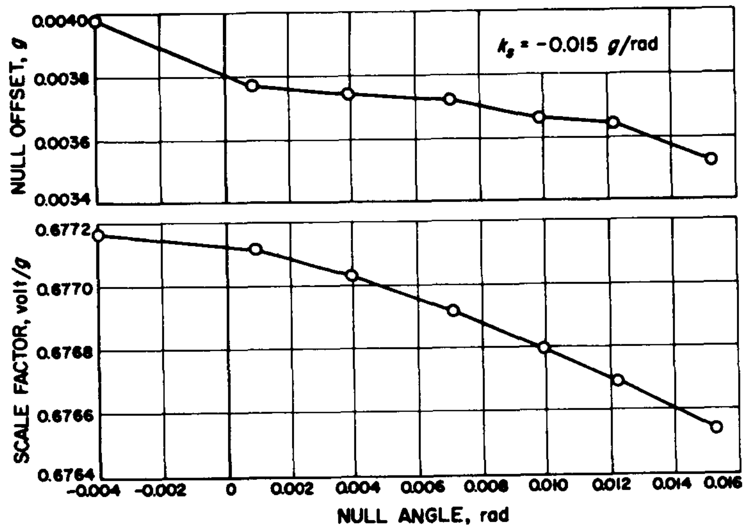

Fig. 14. Null Offset and Scale Factor as a Function of Pendulum Position

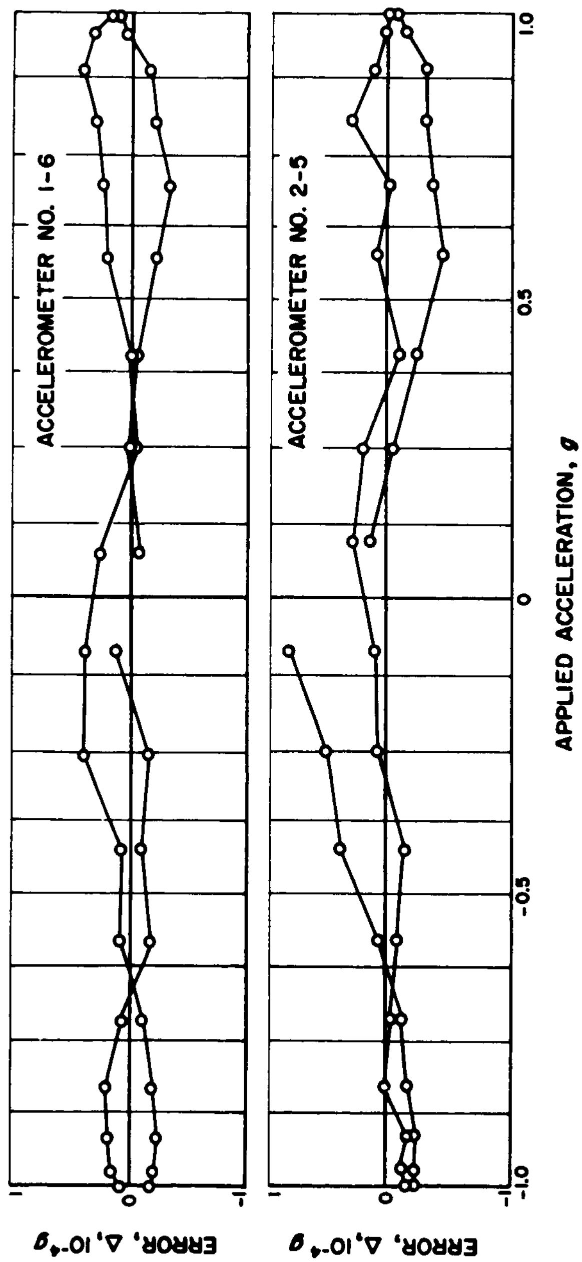

Fig. 15. Linearity Error Curve, Below 1 g for Two Units

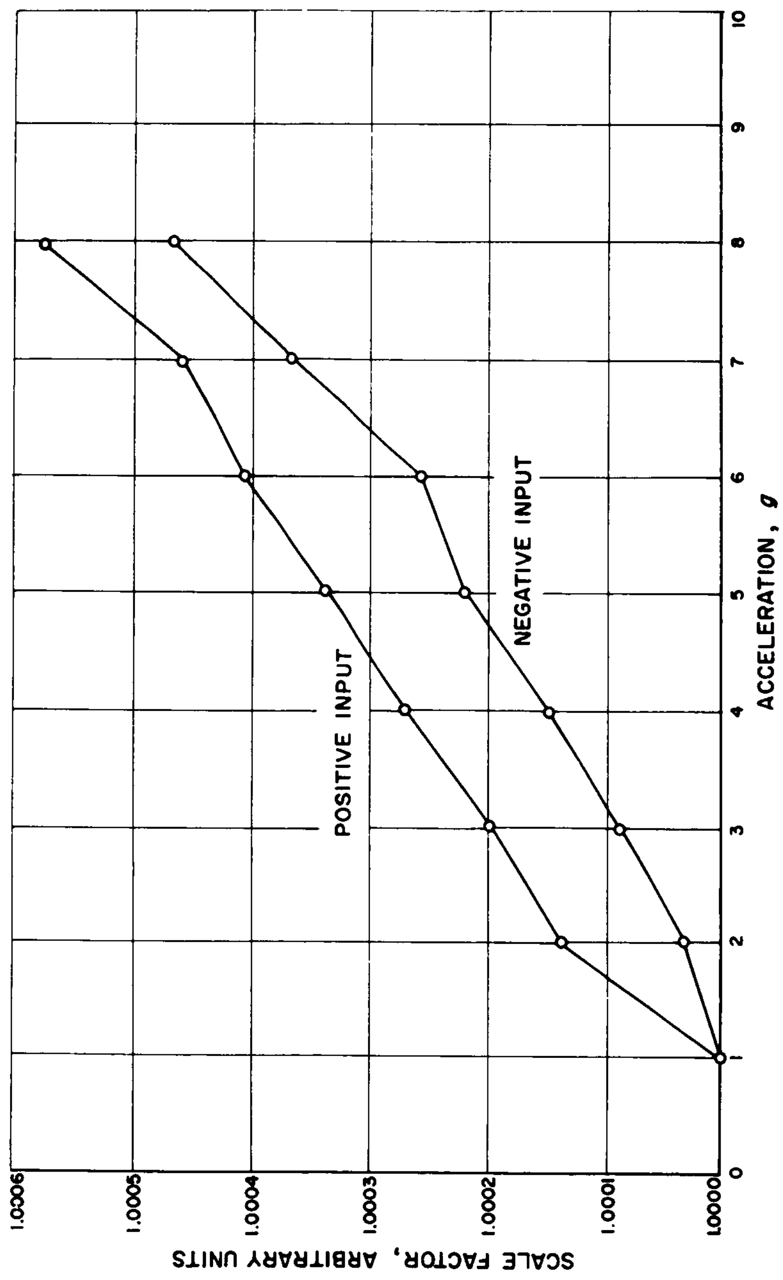

Fig. 16. Scale Factor Change vs Applied Acceleration, as Measured on a Centrifuge